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G. P. St. CLAIR, *Editor*

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions

In This Issue

Page

Comments on the Hydrometer Method of Mechanical Analysis 93

Effect of Curing Conditions on the Strength of Concrete Mortar 106

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COMMENTS ON THE HYDROMETER METHOD OF MECHANICAL ANALYSIS

Reported by R. C. THOREEN, Junior Highway Engineer, Division of Tests, United States Bureau of Public Roads

THE DISCUSSIONS comprising this report are suggested by the subgrade soil investigations of the United States Bureau of Public Roads conducted at its laboratories in Arlington, Va., supplemented by data obtained by the author when engaged as assistant in the cooperative subgrade soil research carried on at the Engineering Experiment Station of the Ohio State University, Columbus, Ohio.

The hydrometer method of mechanical analysis, the procedure for which has been published in PUBLIC ROADS (1)[1] has two distinct advantages when used in subgrade soil investigations: First, an analysis by this method requires a minimum of time and effort; and, second, such an analysis furnishes the data required for the construction of a complete particle-size accumulation curve. This, in turn, discloses the percentage of particles of any desired size, whereas with other methods greater effort is required to obtain information on only the sand, silt, and clay contents.

The hydrometer method consists of two operations—the determination of the percentage of suspended soil from hydrometer readings corrected for the particular test conditions and the determination by means of Stokes's law of the maximum particle size corresponding to a particular percentage of suspended soil.

HYDROMETER METHOD GIVES SATISFACTORY RESULTS IF CAREFULLY APPLIED

Readings of a sensitive hydrometer in soil suspensions give results sufficiently accurate for the determination of the grain size distribution in subgrade soils.

Thorough dispersion of the soil sample is desirable. Apparatus highly efficient for this purpose is now in use.

A high degree of deflocculation is also of importance. Sodium silicate has been found the most satisfactory deflocculating agent.

In the use of Stokes's formula to determine grain size distribution, it is necessary to obtain by experimental methods approximate values for L, the average depth to which soil particles settle in a given time. Satisfactory results were obtained with a value of L equal to 0.42 of the total immersed depth of the Bouyoucos hydrometer, and with a value equal to the depth of the center of volume of the specific gravity hydrometer.

With these values of L, test results were found to be in substantial agreement with the more elaborate pipette method of making the mechanical analysis.

The errors involved in the use of a sensitive hydrometer are subordinate to those due either to partial deflocculation or to the assumptions involved in the use of Stokes's law.

The errors of the hydrometer method are those common to all methods utilizing sedimentation.

The relation between the hydrometer reading and the percentage of suspended soil is expressed by the formula:

$$P = \frac{(R + \Delta R)a}{W} \times 100 \quad \text{---------- (1)}$$

where

R = hydrometer reading.
W = weight of soil originally dispersed per liter of suspension.
ΔR = correction to hydrometer reading for variation in temperature from 67° F.
a = correction coefficient for variation in specific gravity from 2.65.
P = percentage of originally dispersed soil remaining in suspension.

The maximum grain size in suspension at any given time after dispersion, according to Stokes's law, is expressed by the formula:

$$d = \sqrt{\frac{30nL}{980\ (G - G_1)\ T}} \quad \text{---(2)}$$

where

d = maximum grain diameter in millimeters.
n = coefficient of viscosity of the suspending medium, in poises.
L = average distance in centimeters through which soil particles settle in a given time.
T = period of sedimentation, in minutes.
G = specific gravity of soil particles.
G_1 = specific gravity of the suspending medium.

The values of the nine variables—n, L, T, G, G_1, R, W, ΔR, and a—must be available before the percentage of soil in suspension, P, by means of equation 1, and the corresponding grain size, d, by means of equation 2, can be determined.

Both the specific gravity, G_1, and the coefficient of viscosity, n, of the suspending medium, in this case water, are furnished by the Smithsonian Physical Tables (2).

The hydrometer readings, R, corresponding to different times of sedimentation, T, are observed as part of each test. This is true also of the weight of soil dispersed, W, and the specific gravity of the soil particles, G.

This leaves the specific-gravity correction coefficient, a, the temperature correction, ΔR, and the assumed

[1] Figures in parentheses refer to reports listed in the bibliography attached to this report.

distance of particle settlement, L, to be determined by research before formulas 1 and 2 can be used in a complete procedure for making the mechanical analysis of soils by the hydrometer method. Accordingly, investigations for determining these values were begun early in 1928.

These investigations resulted in the development of a test procedure equally applicable to the Bouyoucos hydrometer and to any sensitive hydrometer calibrated in specific gravities, and provided correction coefficients whereby both the grams per liter concentration and the maximum particle diameter corresponding to the hydrometer readings could be determined. In addition, they demonstrated the fact that the results furnished by the hydrometer method check within practical limits those obtained by the pipette method of the United States Bureau of Chemistry and Soils, and other methods. As a further outgrowth of this work, a new and effective deflocculating agent was introduced and both a new type of hydrometer and a revised dispersing cup and stirring paddle were developed.

The test procedure, as noted above, has been published. Comments on the test procedure and the hydrometer calibration, comparisons of results furnished by different methods of mechanical analysis, discussion of the influence of various deflocculating agents, and descriptions of the new hydrometer and dispersing cup and their use, comprise this report.

THE DETERMINATION OF TEST-PROCEDURE REQUIREMENTS

Interested testing engineers may be curious regarding certain of the requirements of the test procedure as published. The purpose of this report is to present additional explanations of these requirements in order to prevent the duplication of the work on which they are based.

The following requirements are among the most important of those specified in the procedure:

1. Soils having a plasticity index between 0 and 5 are dispersed only five minutes in the dispersing apparatus.
2. Soils having a plasticity index between 5 and 20 are pretreated by soaking in water for 18 hours and then dispersed for 10 minutes.
3. Soils having a plasticity index greater than 20 are pretreated with 6 percent hydrogen peroxide, soaked for 18 hours, and then dispersed for 15 minutes.
4. A sodium-silicate solution is used as a deflocculating agent for all soils.
5. The hydrometer is read at the top of the meniscus formed around its stem.
6. The suspensions are maintained at a constant temperature throughout the test.
7. Readings of the hydrometer are corrected for a suspension temperature other than the standard temperature of the hydrometer.
8. Readings of the hydrometer are corrected for any variation in the specific gravity of the soil from the average or standard specific gravity, 2.65.
9. The depth of settlement, L (equation 2), for the Bouyoucos hydrometer is 0.42 of the distance from the surface of the suspension to the lower end of the hydrometer. The logical and experimental bases of these requirements are discussed in the following paragraphs.

Dispersion.—The results produced by any method of soil analysis based on sedimentation through water depend upon the degree to which the soil particles are dispersed. In the absence of complete dispersion, the rate of settlement will depend upon the sizes of the undispersed aggregates rather than the sizes of the individual particles; and consequently the diameters of accumulations rather than the diameters of individual grains will be indicated.

After the separation of the particles, it is equally important to prevent their flocculating or coalescing into loosely bound aggregates, which settle more rapidly than the individual particles and also lead to error in the size determination.

Soil concretions are more likely to form in the fine-grained than in the coarser-grained soils. Also, the concretions in some fine-grained varieties are likely to offer greater resistance to breaking down than the concretions in other varieties of the fine-grained soils. The colloidal properties which furnish the resistance of aggregations to dispersion are reflected more definitely by the plasticity of the soil than by the fineness of the soil grains.

Thus, a soil with a plasticity index of 8 and a clay content of 77 percent[2] may disperse much more readily than a soil with a plasticity index of 32 and a clay content of but 23 percent.[3]

The higher the plasticity index the greater is likely to be the effort required to disperse the soil. Consequently, it is only natural to disperse soils with high plasticity indices for a longer period than those having little or no plasticity.

The highly efficient dispersing apparatus referred to in the article on test procedure (1) has been found capable of producing the required degree of dispersion of coarse-grained soils (plasticity index, 0 to 5) in 5 minutes. A longer period of dispersion tends to break down the sand grains into smaller fragments and therefore should be avoided.

Moderately plastic soils (plasticity index, 5 to 20) are pretreated by soaking in water for 18 hours before dispersing. The slaking and the softening of the soil aggregations due to this treatment make it possible to disperse these soils properly by agitating for 10 minutes.

The highly plastic soils, with plasticity indices exceeding 20, are likely to contain aggregations very difficult to break down. These soils are treated with hydrogen peroxide prior to the soaking for 18 hours. This pretreatment of the sample separates the aggregated particles to such an extent that a mixing period of 15 minutes is sufficient to produce the desired degree of dispersion. The effect of the hydrogen peroxide pretreatment is shown in table 1.

TABLE 1.—*The effect of hydrogen-peroxide pretreatment on the mechanical analysis of fine-grained soils*

Soil no.	Percentage of sample dispersed			
	No pretreatment; particles finer than—		Hydrogen peroxide pretreatment; particles finer than—	
	0.005 mm	0.002 mm	0.005 mm	0.002 mm
763	34.2	21.5	36.8	26.0
791	37.5	18.5	40.5	21.0
872	40.0	23.0	44.4	25.5
695	46.5	31.0	48.7	35.0
837	73.5	62.2	75.4	64.5
802	75.5	48.0	78.0	53.5

[2] See sample no. 6, tables 15 and 16, p. 141, PUBLIC ROADS, vol. 12, no. 5, July 1931.
[3] See sample no. 7, tables 17 and 18, p. 142, PUBLIC ROADS, vol. 12, no. 5, July 1931.

SODIUM SILICATE FOUND BEST DEFLOCCULANT

Deflocculation.—Extensive tests with various deflocculating agents showed sodium silicate to be the most effective for maintaining separation of the dispersed soil particles in suspension. The other reagents tested are those commonly used for deflocculation of soil suspensions and include potassium hydroxide, ammonium hydroxide, sodium carbonate, and sodium oxalate. Results obtained from hydrometer analyses on duplicate samples of four soils treated with the different reagents are shown in table 2. All the samples were dispersed for equal periods, and, as indicated in table 2, the reagents were used in the amounts required to make the suspensions equinormal.[4]

TABLE 2.—*Total percentages of various sizes obtained by treatment with different dispersing agents*

Soil no.	State	No reagent			Potassium hydroxide 5 cc N/1 solution			Sodium carbonate 5 cc N/1 solution			Sodium oxalate 10 cc N/2 solution			Sodium silicate 5 cc N/1 solution		
		Percentage of particles finer than—														
		0.005 mm	0.002 mm	0.001 mm	0.005 mm	0.002 mm	0.001 mm	0.005 mm	0.002 mm	0.001 mm	0.005 mm	0.002 mm	0.001 mm	0.005 mm	0.002 mm	0.001 mm
5792	Iowa	1.5	(1)	(1)	18.5	[2] 5.0	[2] 2.0	20.0	12.0	[2] 7.0	22.0	17.0	15.0	22.0	17.5	15.5
5853	Miss.	50.0	(1)	(1)	66.5	22.5	14.0	82.0	43.0	28.0	78.0	59.5	50.0	87.0	67.0	56.5
6054	N.C.	(1)	(1)	(1)	23.0	[2] 6.0	[2] 3.0	37.0	[2] 8.0	(1)	29.0	[2] 7.0	[2] 3.0	38.0	27.0	22.5
6278	Texas	[2] 9.0	[2] 6.0	(1)	19.0	[2] 1.0	(1)	[2] 40.0	[2] 4.0	[2] 1.0	64.0	34.0	(1)	62.0	45.0	29.0

[1] Completely flocculated.
[2] Partially flocculated.

In this case the degree of normality was equal to that furnished by 5 cc of a 1-normal (N/1) solution in a liter of suspension. Due to its low solubility, the sodium oxalate had to be used in a half-normal (N/2) solution. This required 10 cc of the sodium oxalate half-normal solution per liter to make the suspension equinormal with the suspensions containing 5 cc of the 1-normal potassium-hydroxide, sodium-carbonate, and sodium-silicate solutions.

The sodium-silicate solution specified in the procedure is prepared by dissolving chemically pure crystals in sufficient water to give the desired density of 3° Baumé. In the absence of a Baumé hydrometer, the density may be conveniently measured with a Bouyoucos hydrometer, which at 67° F. should read about 36.5 gram divisions at the proper dilution, or with a specific gravity hydrometer, which, if calibrated at 67° F., should read about 1.023.

The properties of the sodium-silicate crystals used are as follows (3): Grayish white in color; formula as identified by the melting point of 48° C., $NaSiO_3 \cdot 9\,H_2O$ (sodium metasilicate); loses 6 H_2O at 100° C.

Reading the hydrometer.—Because of the turbidity of the suspension, the hydrometer is read at the top of the meniscus which rises on the stem. This differs from the usual practice of reading the hydrometer through the liquid, at the point where the surface cuts the hydrometer scale. For this reason each reading would be too small by an amount equal to the height of the meniscus were the suspending medium pure distilled water. Such being the case, a correction equal to the height of the meniscus or approximately 1 division on the hydrometer scale (1 gram per liter) would have to be added to each reading.

In our case, however, the density of the suspending medium is increased by the silicate solution a constant amount equal to a specific gravity of 0.0005 or approximately 0.8 gram per liter. This correction is subtractive and balances for all practical purposes the additive correction of approximately 1 gram per liter referred to above.

The top of the meniscus may be accurately discerned by placing the source of illumination so as to cause a reflection or high light at that point.

It is essential that the hydrometer be kept clean while in use, as grease or soil on the stem will prevent the proper formation of a meniscus, thus making accurate readings difficult to obtain, and causing lag of the instrument. Also, soil accumulating on the bulb will cause erroneous readings.

Constant-temperature bath.—Since the velocity with which a grain of given diameter will settle is a function of the viscosity of the suspending medium and this in turn is dependent on the temperature, it is evident that if n, the coefficient of viscosity (equation 2), is kept a constant throughout the test a more accurate solution of this formula is possible than will be the case if n is a variable. Changes in temperature in the soil suspension also cause convection currents which interfere with the free fall of the particles. Finally, hydrometers should be used at temperatures as close as possible to that at which they were calibrated, in order to avoid errors due to thermal expansion or contraction of the hydrometer bulb.

In view of these facts the soil suspension should be maintained at a uniform temperature which is as close to the standard temperature as is possible without undue refinement of apparatus.

The temperature correction.—The necessary correction of any hydrometer reading for a variation from the standard temperature is determined by the accompanying change in the density of the water. For a specific gravity hydrometer the correction is equal to the difference between the density of water at the standard temperature and the density at the temperature of the suspension under test.

For the Bouyoucos hydrometer, the temperature correction, ΔR (equation 1), is determined by dividing the difference between the density of water at the test temperature and at 67° F. by the density change equivalent to one division on the hydrometer scale.

The density of the suspension when a properly calibrated Bouyoucos hydrometer reads 0.0 is 0.9984, the density of water at 67° F. The density of the suspension for a hydrometer reading of 50 grams per liter equals 1.02956.

Thus the total change in density for the 50 divisions on the hydrometer scale is $1.02956 - 0.99840 = 0.03116$; and the difference for each gram per liter division on the hydrometer scale equal 1/50 of 0.03116 or 0.000623.

The derivation of the corrections for temperature at 10° intervals between 40° F. and 100° F. are given in table 3, and the correction curve (fig. 1) is based on the values in the last column of this table.

The corrections obtained from this curve apply to a hydrometer which reads 0.0 (at the water surface, not at the top of the meniscus) in distilled water at 67° F., the nominal standard temperature for the Bouyoucos

[4] A normal solution (written N/1 or 1 N) is one which contains, in a liter of solution, a number of grams of the dissolved substance equal to the molecular weight divided by the number of replaceable hydrogen atoms or their equivalent. Thus, a normal solution of potassium hydroxide, KOH, molecular weight 56, contains 56 grams per liter of solution, since it has one hydrogen equivalent, K. A solution of sodium carbonate, Na_2CO_3, molecular weight 106, contains 53 grams per liter of solution, a number equal to one half the molecular weight, since it has two hydrogen equivalents, Na_2.

hydrometer. Actually, the reading at 67° F. is likely to vary among different hydrometers [5] in which event this reading, if greater than 0.0, must be subtracted from each of the temperature corrections; if less than 0.0, it must be added.

The reading to be added or subtracted is the reading of the Bouyoucos hydrometer in distilled water at 67° F. The correction curve is then plotted a corresponding number of divisions to the right of 0 correction when the reading is positive and to the left of this location when the reading is negative.

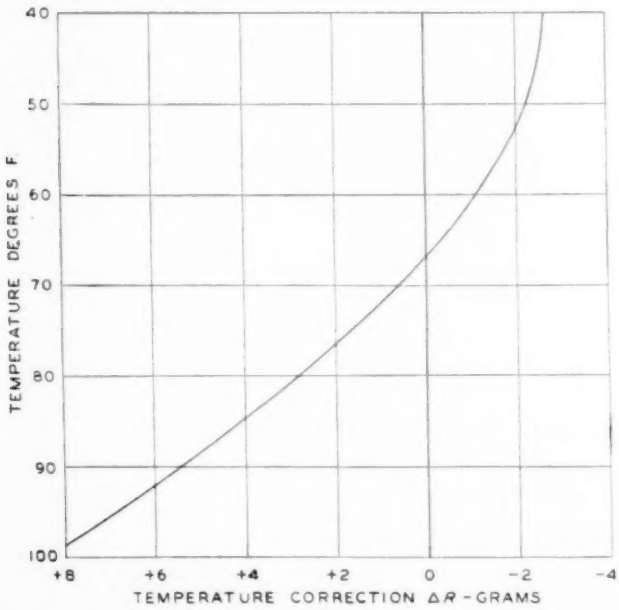

FIGURE 1.—TEMPERATURE CORRECTION CURVE FOR THE BOUYOUCOS HYDROMETER READING.

As an alternate method, the temperature correction curve may be determined by reading the hydrometer in distilled water at successive temperatures between 40° F. and 100° F.

TABLE 3.—*Derivation of temperature corrections for the Bouyoucos hydrometer readings*

Temperature	Density of water	Difference from density at 67° F.	Equivalent number of divisions on the hydrometer scale, $\frac{\text{Diff.}}{0.000623}$	Temperature correction
°F.				
40	0.9999986	0.0016428	2.63	−2.6
50	.9997282	.0013724	2.20	−2.2
60	.9993343	.0006785	1.09	−1.1
67	.9983558	.0000000	0.00	0.0
70	.9980016	.0003542	0.56	+0.6
80	.9966273	.0017285	2.76	+2.8
90	.9949920	.0033638	5.38	+5.4
100	.9930691	.0052867	8.46	+8.5

Calibration of the hydrometer scale.—This operation may be accomplished, if desired, by comparing the readings of the Bouyoucos hydrometer with those of standard density hydrometers, or with the densities of standard solutions. For this purpose the relation between the grams of soil per liter and the corresponding density of the suspension must be determined.

[5] Among seven hydrometers used by the writer in the cooperative subgrade soils laboratory at Ohio State University, this reading varied from 0.0 to −1.5.

The density of a soil suspension equals, in c.g.s. units,

$$\frac{\text{weight of water} + \text{weight of suspended soil}}{\text{volume of water} + \text{volume of suspended soil}}$$

This may be formulated as follows:

$$D = \frac{G_1\left(V - \frac{w}{G}\right) + w}{V} \qquad (3)$$

In which D = density of suspension.

V = volume of suspension in cubic centimeters.
w = weight of suspended soil, grams.
G_1 = density of water.
G = specific gravity of soil.

Substituting 1,000 for V, 2.65 for G, and 0.9984 for G_1, we have,

$$D = \frac{0.9984\left(1{,}000 - \frac{w}{2.65}\right) + w}{1{,}000}$$

$$= \frac{w}{1604.5} + 0.9984 \qquad (4)$$

$$\text{and } w = 1604.5\ (D - .9984) \qquad (5)$$

Equation 5 expresses the basic relation between the grams of soil per liter of suspension and the density for standard test conditions.

Since the Bouyoucos hydrometer is proposed to show the grams per liter under these conditions, equation 5 should express also the relation between the hydrometer readings and the corresponding densities of the suspensions.

The calibration curve of the hydrometer scale, therefore, is the curve which expresses the relation of the observed readings to the values of w computed according to equation 5.

On the basis of the relation between density of suspension and weight of suspended soil, expressed in equation 5, the percentage of originally dispersed soil per liter corresponding to a given density of suspension may be determined from equation 1 by substituting for the quantity $R + \Delta R$ (which equals w for a specific gravity of 2.65) the equivalent value of w in terms of density, $1604.5\ (D + \Delta D) - 0.9984$, in which ΔD equals the correction of the density for a temperature other than 67° F. When this substitution is made, equation 1 becomes

$$P = \frac{1604.5[(D + \Delta D) - 0.9984]a}{W} \times 100 \qquad (6)$$

For example, for the values

$D + \Delta D = 1.0248$, $a = 1.05$, and $W = 50$

$$P = \frac{1604.5(1.0248 - 0.9984)1.05}{50} \times 100 = 88.95 \text{ percent}$$

Specific gravity correction.—Since for a given weight of soil dispersed, the density of the suspension varies with the specific gravity of the soil, the readings of the Bouyoucos hydrometer must also be corrected for a soil gravity other than 2.65 in order to determine the

true grams per liter concentration. The necessity for this correction was first noted in the cooperative subgrade soils laboratory at Ohio State University when the writer attempted to make hydrometer tests on three paint pigments with specific gravities ranging from 4 to 5.5. As a result of the high specific gravities, the 1-minute readings in suspensions of 50 grams per liter ranged from 57 to 62.5.

Since the hydrometer reading for any given weight of suspended soil is determined by the difference between the density of water and that of the soil suspension, readings in a suspension of soil having a gravity other than 2.65 must be corrected in proportion as this difference, or density range, varies from that of a suspension of an equal weight of soil of gravity 2.65.

If the specific gravity, G, of the soil is greater than $G_0 = 2.65$, the reading of the hydrometer will be such as to give, if uncorrected, a percentage of soil in suspension which exceeds the correct percentage in proportion as the density range exceeds the density range under standard conditions (i.e., when $G = G_0 = 2.65$). The specific gravity coefficient a is therefore defined by the ratio

$$a = \frac{D_0 - G_1}{D - G_1}$$

where

D = density of suspension.

D_0 = density of suspension under standard conditions.

Substituting the expression for density of suspension given in equation 3, we have

$$D - G_1 = \frac{G_1\left(V - \frac{w}{G}\right) + w}{V} - G_1$$

$$= \frac{w(G - G_1)}{GV}$$

Similarly, for standard conditions

$$D_0 - G_1 = \frac{w(G_0 - G_1)}{G_0 V}$$

The value of a is therefore given by the expression

$$a = \frac{D_0 - G_1}{D - G_1}$$

$$= \frac{w(G_0 - G_1)}{G_0 V} \times \frac{GV}{w(G - G_1)}$$

$$= \frac{G_0 - G_1}{G_0} \times \frac{G}{G - G_1}$$

Since $G_0 = 2.65$ and $G_1 = 0.9984$,

$$a = \frac{2.6500 - 0.9984}{2.6500} \times \frac{G}{G - 0.9984}.$$

The curve of the values of a for specific gravities between 2.00 and 3.00 is shown in figure 2.

This correction of the hydrometer reading for determining the percentage of soil in suspension was expressed in tabular form in the procedure published in PUBLIC ROADS, vol. 12, no. 8. It should not be confused with curve C, figure 3, in the same publication,

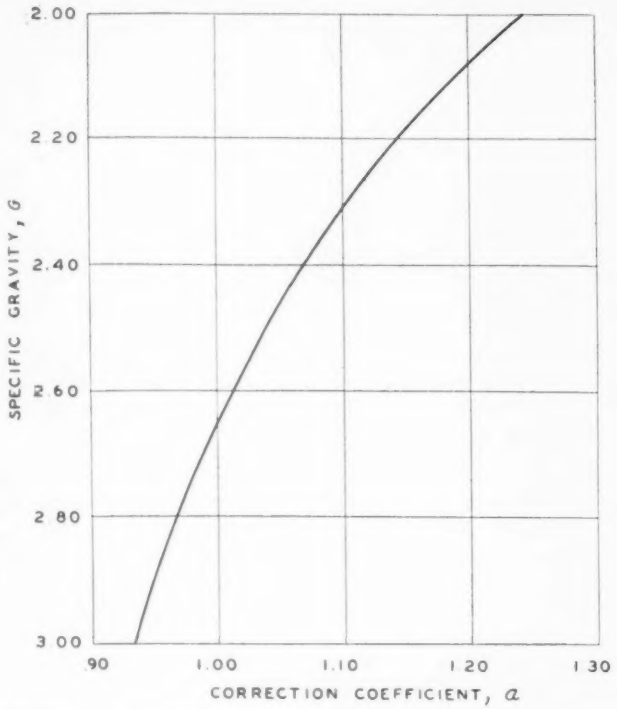

FIGURE 2.—SPECIFIC GRAVITY CORRECTION CURVE FOR HYDROMETER READING.

which shows specific gravity corrections to be used for determining the soil particle size.

The distance of particle settlement, L.—It is well to recall at this point that the hydrometer method of analysis consists of two separate and distinct operations: (a) The determination of the percentage of soil in suspension after any period of sedimentation and (b) the determination of the corresponding maximum grain size.

The preceding discussion has brought out the fact that the determination of the percentage of the soil in suspension is made according to well established physical laws and hence can be considered in the nature of an exact operation.

In contrast, the use of Stokes's law in the determination of particle size, requires so many assumptions that the value of L becomes entirely arbitrary and can be determined only by comparison with other methods of determining grain size.

BASIC ASSUMPTIONS OF STOKES'S LAW DISCUSSED

A brief statement of the assumptions embodied in the use of Stokes's formula and their validity will serve to make clear its limitations, especially when applied to the hydrometer method of soil analysis. These assumptions, according to Searle (4) and Keen (5), are as follows:

1. The particles of solid matter are much larger than the particles of the liquid. This holds true for only those particles whose size is not so minute that they begin to show Brownian movement.

2. The liquid is of infinite extent in comparison with the settling particles, i.e., the motion is not affected by the proximity of the containing walls or of neighboring particles. Usually the vessel is large enough to overcome the effect of the containing walls, but high concentrations of suspended soil may interfere with the free fall of the particles.

3. The particles are smooth and rigid spheres. Soil particles can be considered rigid, but they are not necessarily smooth, and are rarely spherical.

4. No slipping occurs between the particles and the liquid. This assumption can be taken as correct, since soil particles are wetted by water.

5. The settling velocity of the particles is small. This can be considered true, as only the smaller particles (with low settling velocities) are usually considered, those of larger size being graded by means of sieves rather than on the basis of their settling velocities.

6. The particles are small, but not excessively so, since those of colloidal size are influenced by their Brownian movement. Stokes's formula is not applicable to colloidal particles unless corrected by a factor depending on the collisions between particles, a correction which is not usually made.

7. The particles settle as individuals and not as aggregations, such as may be formed due to flocculation. Flocculation may usually be prevented by use of a chemical reagent; an apparently deflocculated suspension, however, may contain some flocculated clay particles not discernible by ordinary means, which will lead to error because the aggregations do not settle at a normal rate, and may absorb and carry with them fine sand and silt particles.

8. The coefficient of viscosity of the suspending medium is assumed as being that of water. As a matter of fact the viscosity may vary from that of water because of soluble material in the soil, unless this is first removed by washing, or because of the presence of colloidal material fine enough to remain suspended indefinitely.

9. A suspension at any given depth, L, after a given time, T, contains: (a) no particles whose velocity of fall exceeds L/T, and (b) in the same concentration as when originally dispersed, all particles with a velocity of L/T or smaller.

Therefore, at a given time, T, the suspension at any depth, L, is assumed as representative of the original concentration of that portion of the soil particles smaller than a particular maximum grain size whose velocity of fall is L/T. This assumption is not strictly true, because in high concentrations the fall of the large particles is likely to increase the fall of the smaller particles by contact; and in the same manner the smaller particles are likely to decrease the rate of fall of the larger particles.

10. There is a plane of maximum grain size at a depth, L, representative of the percentage of soil in suspension revealed by the hydrometer.

Such a plane exists, but its location with respect to the position of the hydrometer varies with the shape of the hydrometer and the grading of the soil. Therefore, any selected value of L can only be considered as indicating the average position of this plane for all soils and this must be determined by trial.

To make the results obtained by the hydrometer method agree with those furnished by any other method, it is only necessary to substitute in equation 2 those values of L which indicate for a given percentage in suspension the same maximum grain sizes as are indicated by the other method of analysis.

VALUE OF *L* DETERMINED BY COMPARISON WITH PIPETTE METHOD

In the present instance it was desired to determine that value of L which, when substituted in Stokes's formula, indicates for given percentages in suspension the same maximum grain sizes as those indicated by the pipette method of the Bureau of Chemistry and Soils. This was desired, not because the agronomists' classifications are directly applicable for use in subgrade surveys but because of the great amount of available published information on soil surveys made by that Bureau and the very important part the mechanical analysis plays in its soil classification.

In the first investigation at Arlington, L was tentatively assumed to equal the distance from the surface of the suspension to the location of the center of volume of the hydrometer system in the suspension.

Tests in the laboratory of the Bureau of Public Roads disclosed that the clay contents indicated by the use of this value of L agreed fairly well with those indicated by a method formerly used by the Bureau of Chemistry and Soils (6). They were appreciably smaller, however, than the clay contents indicated by the pipette method now used by the Bureau of Chemistry and Soils (7). Consequently, a second trial value of L was investigated.

Since at any time after the beginning of the test the density varies from top to bottom, it seemed logical to assume that the required maximum diameter will be located at the plane where the density is equal to the average density of that portion of the suspension supporting the hydrometer.

Additional investigation in the laboratory of the Bureau of Public Roads, by means of pipette extractions, disclosed that the plane of average density of the portion of the suspension supporting the hydrometer varies from 0.33 for some soils to 0.50 of the distance from the surface of the suspension to the bottom of the hydrometer for other soils. Therefore a value of L equal to 0.42 of the immersed depth of the hydrometer may be taken as the average distance from the surface of the suspension to the plane of average density of that portion of the suspension supporting the hydrometer. This value was selected as a second trial value of L.

The hydrometer method, with this new value of L, gave results in substantial agreement with those obtained by the Bureau of Chemistry and Soils.

TABLE 4.—*Comparison of the corrected Bouyoucos hydrometer reading with the concentration in grams per liter at the reference point*

Soil no.	Time	Hydrometer reading	Grams per liter at 0.42 of distance from surface to bottom of hydrometer
	Hours		
4056	1	28.0	27.0
	4	22.0	23.0
	24	10.5	11.0
4281	1	43.0	42.5
	4	32.5	33.5
	24	17.0	15.6
602	1	14.2	12.5
	4	9.3	7.5
	24	4.0	3.5
683	1	13.5	12.0
	4	9.1	8.0
	24	6.2	5.0
720	1	20.4	20.8
	4	15.4	15.4
	24	11.7	10.5
770	1	23.0	21.8
	4	17.9	16.5
	24	11.2	10.5
808	1	21.9	21.0
	4	17.6	17.3
	24	12.8	10.7
842	1	15.8	15.0
	4	13.5	12.0
	24	10.0	9.4
965	1	25.7	26.0
	4	19.3	19.0
	24	10.8	11.0

As illustrated in table 4, the agreement between the corrected hydrometer reading and the concentration in grams per liter indicated by pipette extractions was found to substantiate the assumption that the plane of the average density of that portion of the suspension holding the hydrometer is located a distance from the top of the suspension equal to the selected value of L.

Subsequently a third investigation of the required value of L was made. In this case the hydrometer reading R, required to give the percentage of a particular fraction (e.g., clay, 0.005 mm) obtained by the pipette method was determined from equation 1 by substituting the percentage, P, of the fraction, together with the necessary temperature and specific gravity corrections, ΔR and a, and weight of soil, W, used in the hydrometer test. The time interval, T, corresponding to this reading was then determined from the curve of original hydrometer readings plotted against time. With this value substituted for T, and the particular grain diameter substituted for d, Stokes's formula was then solved for L, the depth of settlement. The ratio of this depth to the immersed depth of the hydrometer gave L as a fraction of the distance from the surface of the suspension to the bottom of the hydrometer.

A number of determinations made in this manner by use of hydrometer test data in conjunction with results furnished by the Bureau of Chemistry and Soils gave an average value for L equal to 0.419 of the immersed depth of the hydrometer. Since this value agreed with the selected value of L, equal to 0.42 of the immersed depth, the latter, which had now been in use for some time, was adopted for use in the procedure as published.

DEPTHS OF SETTLEMENT OF GRAINS OF A PARTICULAR DIAMETER

According to Stokes's law L, the distance of particle settlement, is a function of T, the time of settlement. Therefore, the distance of settlement for grains of any particular diameter may be expressed also in terms of T.

The values of T corresponding to the values of L selected for use in the Bureau of Public Roads procedures (8) vary between 43.5 and 75.6 minutes for the determination of the total clay content (0.005 to 0 mm) and between 272 and 473 minutes for the determination of the fine clay content (0.002 to 0 mm) for hydrometer readings of 60 and 0, respectively.

To accomplish the same results Bouyoucos (9) suggested that a time, T, of 1 hour, be used to determine the total clay content and a time of 2 hours be used to determine the fine clay content. Eno (10) suggested a time, T, of 60 minutes for the total clay content and 370 minutes for the fine clay content.

In addition, times varying from 57.5 to 137.2 minutes (depending on the depth of the hydrometer) for the total clay content, and from 359 to 857 minutes for the fine clay content, were found in the first investigation of the method by the Bureau of Public Roads, in which the reference plane was assumed to be located at the center of volume of the hydrometer system.

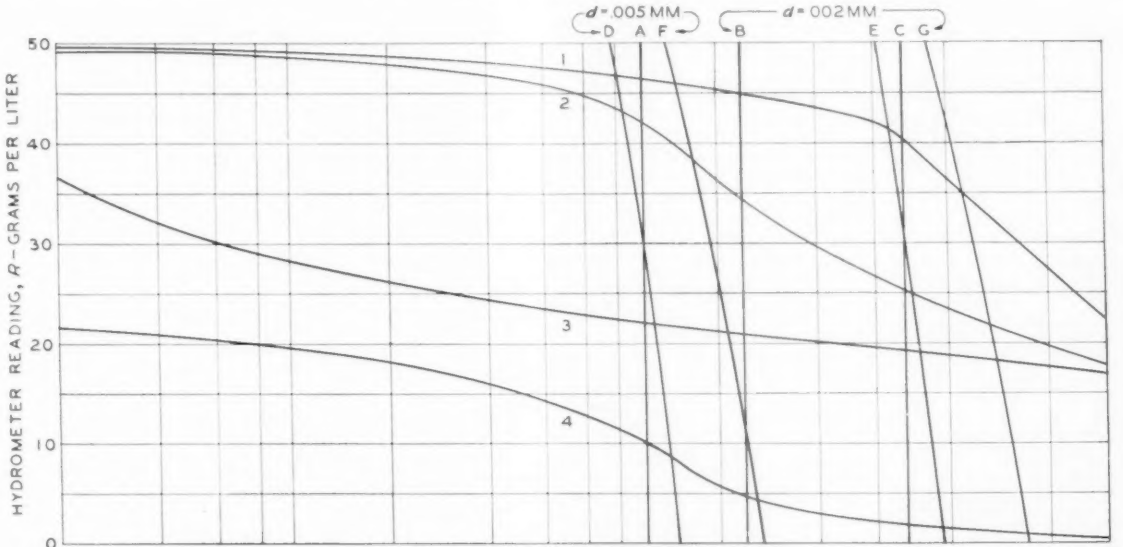

FIGURE 3.—VARIOUS TIMES OF SEDIMENTATION FOR CLAY AND FINE CLAY.

The depths of settlement, L, of the clay and fine clay particles, corresponding to the various values of T referred to above, as computed for standard test conditions, are shown in table 5.

TABLE 5.—*Distance of Settlement, L, of clay and fine-clay particles for various suggested times, T*

Clay: Particles finer than 0.005 mm		Fine clay: Particles finer than 0.002 mm	
T	L	T	L
Minutes	*Centimeters*	*Minutes*	*Centimeters*
60	7.93	120	2.53
43.5	5.75	370	7.83
75.6	10.00	272	5.75
57.5	7.60	473	10.00
137.2	18.15	359	7.60
.....	.....	857	18.15

The significance of the use of the different suggested times of sedimentation for determining the clay and fine-clay fraction is illustrated in figure 3, which shows the relation between hydrometer reading, time of sedimentation as a function of L, and grain diameters of 0.005 mm and 0.002 mm. Line A indicates the time of

sedimentation for clay (0.005 mm) suggested by Bouyoucos and Eno. Line B is the time of sedimentation for fine clay (0.002 mm) suggested by Bouyoucos; and line C the time for fine clay suggested by Eno. These three lines give constant grain diameter for all positions of the hydrometer.

Lines F and G indicate the times of sedimentation for clay and fine clay corresponding to values of L equal to the distance from the surface of the suspension to the center of volume of the hydrometer, as used in the first investigations by the Bureau of Public Roads.

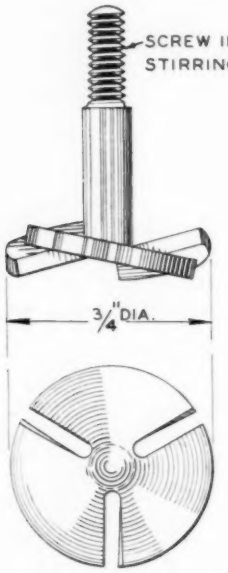

FIGURE 4.—DETAIL OF STIRRING PADDLE.

Lines D and E indicate the times of sedimentation for the clay and fine-clay fractions corresponding to the values of L equal to 0.42 of the distance from the surface of the suspension to the bottom of the hydrometer as specified in the Bureau's procedure.

As compared with curve A (60-minute sedimentation) the times corresponding to the selected L, curve D, figure 3, are such as to indicate higher clay contents for soils with more than about 60 percent of clay; lower clay contents for soils with less than about 60 percent; and the same clay contents for soils with about 60 percent of clay.

For moderately heavy clay soils the clay contents based on the 60-minute reading, line A, figure 3, were in substantial agreement with those indicated by the pipette method. On the same basis, however, the clay contents of very fat clays were indicated to be slightly low and those of very lean soils were indicated to be somewhat high when compared with the results furnished by the pipette method. Therefore, the times (line D) which change with the hydrometer reading indicate clay contents in closer agreement with those indicated by the pipette method than the 60-minute reading (line A).

Curves 1, 2, 3, and 4, figure 3 and table 6, illustrate how the effect of variations in L depends upon the grading of the soil sample. Here it can be seen that L is critical only for those portions of the curves of hydrometer reading against time which slope appreciably. Consequently, if primary interest is in the determination of the clay and the fine clay contents, L is critical for those soils whose curves of hydrometer reading against time slope appreciably in the vicinity of either the 60- or 370-minute ordinates. Thus L is critical for the fine-clay content for the soil curve 1; for both clay and fine-clay content, curve 2; and for the clay content, curve 4.

TABLE 6.—*Percentage of clay (0.005 mm) and fine clay (0.002 mm) as determined by various times of sedimentation. (Fig. 3)*

Soil curve no.	Percentage clay (0.005 mm) according to line—			Percentage fine clay (0.002 mm) according to line—			
	A	D	F	B	C	E	G
1	93.0	93.6	92.0	89.8	81.0	82.8	70.0
2	83.8	86.4	77.0	69.0	50.6	49.8	43.8
3	44.2	44.0	42.0	42.0	38.6	38.0	36.4
4	20.0	17.0	8.6	9.4	3.6	3.0	1.6

NEW APPARATUS DEVELOPED IN CONNECTION WITH THE HYDROMETER INVESTIGATIONS

Improvements in dispersing apparatus.—The stirring paddle furnished with the dispersing apparatus tends to wear out rather rapidly, especially when sandy soils are dispersed. This necessitates frequent changing of the paddle in order that the efficiency of the apparatus shall not be impaired. Furthermore, the paddle

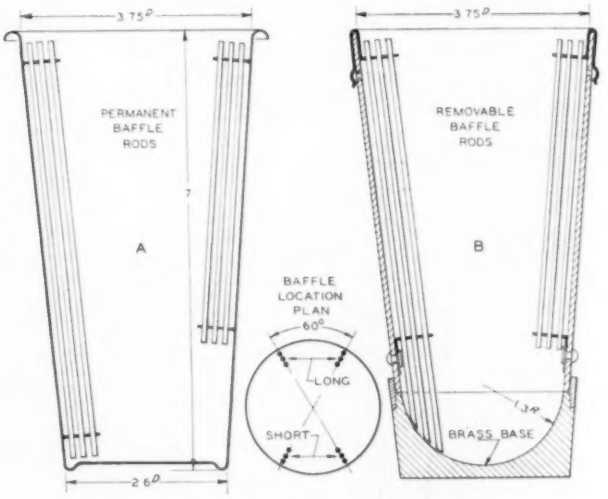

FIGURE 5.—DISPERSION CUPS.

of the dispersing apparatus as purchased is an integral part of the stirring shaft. Therefore, it was necessary to replace the entire stirring rod in order to replace the paddle. A new paddle (fig. 4), made of wear-resisting material and designed to thread into the end of the stirring rod, makes the necessity of replacing paddles less frequent and eliminates the necessity of changing the stirring rod with the paddle.

There was a tendency for some soils to accumulate in the bottom and around the baffles of the original flat-bottom dispersing cup (see fig. 5, left). To overcome this difficulty a new cup with a semispherical bottom and detachable baffles has been recently designed and constructed for use in the Bureau's soils laboratory (see fig. 5, right).

Preliminary tests made with this cup indicate that the shape exerts an influence on the degree of dispersion. In these tests duplicate samples of each of two soils were agitated for equal periods in the two cups and tested with a hydrometer. These periods were purposely

shortened so that the soil would not be completely dispersed and comparative results would be obtained. These results are given in table 7. The higher readings indicate that the concave bottom facilitates dispersion of the soil sample.

TABLE 7.—*Hydrometer readings in suspensions of duplicate samples dispersed (1) in original cup and (2) in cup of new design*

Soil No. 1			Soil No. 2		
Dispersed 5 minutes each			Dispersed 3 minutes each		
Time	Hydrometer reading		Time	Hydrometer reading	
	(1)	(2)		(1)	(2)
5 minutes	40.0	40.9	10 minutes	24.7	25.6
15 minutes	38.5	39.4	1 hour	16.0	18.5
18 hours	26.4	28.0	3 hours	12.0	14.5
42 hours	19.5	21.7	24 hours	6.3	7.8

The new hydrometers.—The new hydrometers for soil analyses developed as an outgrowth of the Bureau's soil investigations are made with a bulb of special shape. These hydrometers are calibrated to read specific gravity directly on the basis of a water density of 1 at 67° F. They are calibrated at this temperature for convenience in comparing test results with those furnished by the Bouyoucos hydrometer. One hydrometer has a range of 0.995 to 1.050 specific gravity, which covers extreme densities of suspensions due to high specific gravities of suspended material or use of large samples. The other two hydrometers cover ranges of 0.995 to 1.020 and 1.015 to 1.040, respectively, and are intended for more accurate analytical work.

The general design of these hydrometers is shown in figure 6, A, which illustrates the first hydrometer mentioned, as compared with the Bouyoucos hydrometer (fig. 6, B). The specific-gravity hydrometers are loaded with mercury confined by a glass septum according to a design patented by the manufacturer. The shape of the bulb is designed to minimize disturbance of the suspension when the hydrometer is inserted or removed.

The percentage of soil in suspension corresponding to a given reading of a specific gravity hydrometer is determined from equation 6, by substituting the hydrometer reading for D. Since the new hydrometers are calibrated on the basis of a water density of 1.0 at 67° F., it is also necessary to substitute this value for the absolute density 0.9984, in the equation. The temperature correction, ΔD, is equal to the difference in the relative density of water at 67° F. and at the temperature of the suspension under test. The curve of temperature corrections for the specific gravity hydrometer is shown in figure 7.

The formula for the percentage of soil in suspension corresponding to a reading of the specific gravity hydrometer is written:

$$P = \frac{1604.5\ (D + \Delta D - 1)a}{W} \times 100 \qquad (7)$$

The value of L for use in the computation of the maximum grain diameter corresponding to a given reading of a specific gravity hydrometer is the distance from the surface of the suspension to the elevation of the absolute center of volume of the hydrometer. This

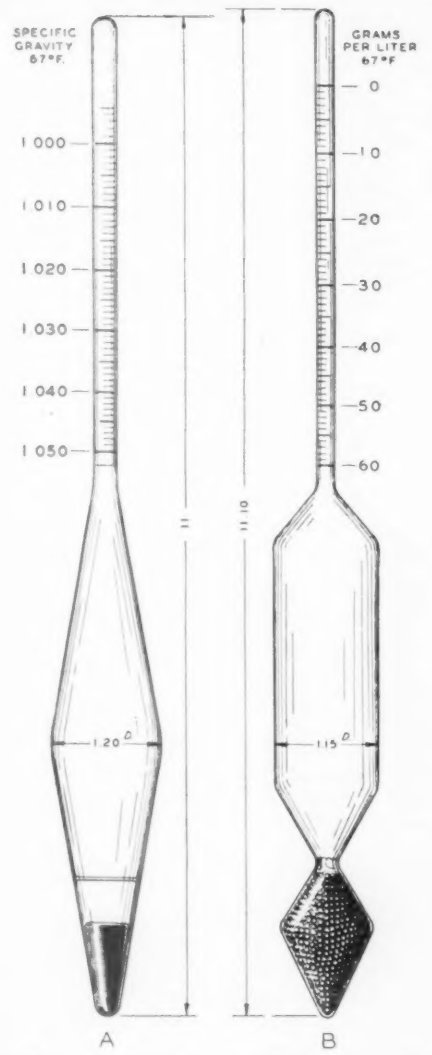

FIGURE 6.—SPECIFIC GRAVITY AND BOUYOUCOS HYDROMETERS COMPARED.

is because the differences between the distances from the surface of the suspension to the absolute center of volume and to the center of volume of the immersed portion of the hydrometer are so small that they do not affect the results appreciably.

Subsequently, it is shown that, probably because of the difference in the shapes of the two hydrometers, results obtained by the use of the specific gravity hydrometer, with L as designated, are in substantial agreement with those furnished by the Bouyoucos hydrometer, with L equal to 0.42 of the immersed depth.

The laboratory test procedure for the specific-gravity hydrometer is the same as that used for the Bouyoucos hydrometer. The formulas given for the determination of the percentages and the grain diameters serve as a basis for the construction of the necessary charts for the graphical solution of the data.

These charts are like those used for solution of the test data obtained with the Bouyoucos hydrometer, except that density values are substituted for grams per liter on the vertical scales, and the curves of time of sedimentation in the chart for the grain diameter determinations are based on the distance to the center of

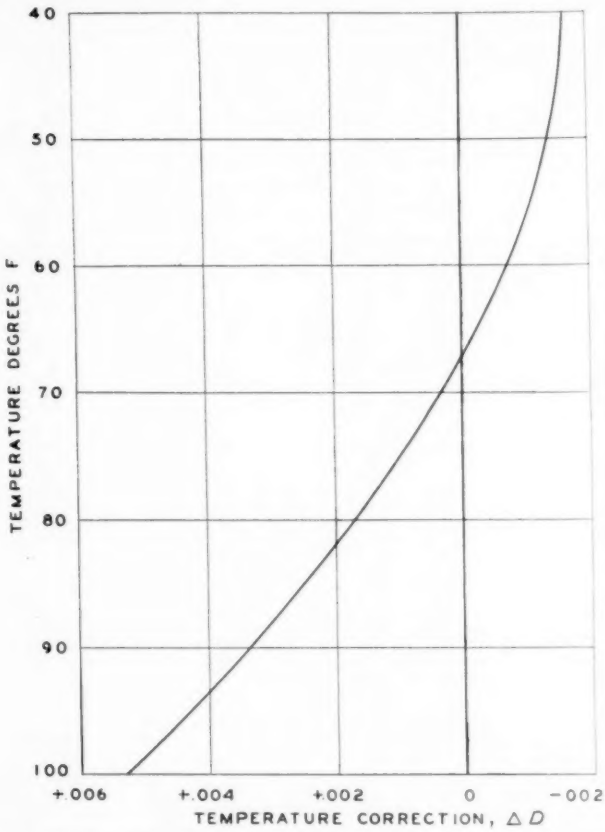

FIGURE 7.—TEMPERATURE CORRECTION CURVE FOR THE SPECIFIC GRAVITY HYDROMETER READING.

volume rather than on 0.42 of the distance to the lower end. With these revised charts the graphical solution may be performed with the same apparatus and in the same manner as in the case of the Bouyoucos hydrometer, as described in the published report on the graphical solution (8).

AGREEMENT OF RESULTS OBTAINED BY DIFFERENT METHODS OF ANALYSIS

As a final step in the mechanical analysis investigation, the results furnished by the hydrometer method were compared with those furnished by three other sedimentation methods.

The sedimentation methods were:

(*a*) The pipette method of the Bureau of Chemistry and Soils.

(*b*) A modified pipette method employed in the laboratory of the Bureau of Public Roads.

(*c*) A beaker method employed at the subgrade soils laboratory of the Ohio State University.

PIPETTE METHOD DESCRIBED

The analyses by the method of the Bureau of Chemistry and Soils were performed in the laboratories of that Bureau. The essential features of this method are as follows: Two samples of that portion of the air-dried soil passing a 2-millimeter screen are weighed out, a 10-gram sample for the analysis and a 5-gram sample for the determintion of hygroscopic moisture.

The 10-gram sample is placed in a 250-cubic centimeter Pyrex electrolytic beaker (diameter 5 cm, height 13 cm) and 6 percent hydrogen peroxide is added in sufficient amount (40 cc or more) to decompose the organic matter. The removal of the organic matter is indicated by a change in color of the soil from dark to light, caused by the removal of the black organic material from the soil. The beaker, containing the sample and peroxide, is warmed in a slow steam bath[6] over night. Then if all organic matter does not appear to have been removed, more hydrogen peroxide of full strength (30 percent) is added. After decomposition of the organic matter, the excess peroxide is boiled off.

The soil sample is then washed as follows: The contents of the beaker are filtered by means of a short Pasteur-Chamberland filter, the residue washed by stirring with 125 cc of distilled water and again filtered, this process being repeated six times. After each filtration the soil adhering to the filter is removed from the filter by applying back pressure, and replaced in the beaker.

Following the last washing, the soil sample is evaporated to dryness and then oven dried at 105° C. for 16 hours (over night). After cooling in a dessicator, the beaker and sample are weighed to the nearest milligram, the difference between the weight and that of the beaker alone being the weight of sample after organic matter and solution loss.

The sample is then transferred to a 250 cc nursing bottle, 10 cc of 0.5 N sodium oxalate solution added as a deflocculating agent, and the volume made up with distilled water to 150 cc. The bottle is then placed in a shaking machine and shaken over night.

When the shaking is completed, the contents are washed through a small sieve fitted with Tyler 300-mesh wire screen cloth (size of openings 0.05 mm, square) into a 1-liter graduated cylinder, which is then filled to the 1-liter mark with distilled water and set aside for sedimentation.

The material remaining on the sieve (sand plus some silt) is dried and weighed and separated by sieves into size classes.

The contents of the sedimentation chamber are stirred with a motor-driven propeller, and by means of a 25-cc automatic pipette a sample is immediately withdrawn before any of the soil particles have had time to settle out. The pipette is emptied into a weighing dish and two or three washings from the pipette added.

The time required for a particle 0.005 mm in diameter to settle 10 cm, is computed from Stokes's formula, using a density of 2.61 and the viscosity of water for various temperatures. From a curve plotted with temperatures as ordinates and time as abscissae, the time for pipetting the clay is determined (77 minutes at 20° C.). At this time the pipette is lowered into the suspension until the tip is 10 cm below the liquid surface, filled by an even suction in about 40 seconds, and the entire contents plus two or three washings are run into a weighing dish.

Pipetting of the fine clay (0.002 mm) is similar to that of the clay except that the settling time is fixed at 6½ hours, the necessary depth being determined from a graph based on Stokes's formula, showing the relation of depth to temperature for this constant time. Weighings of the evaporated and oven-dried pipetted samples are carried to 0.1 milligram.

The results of the analysis are calculated as follows: From the moisture determination of the 5-gram sample, the dry weight of the sample for analysis is computed. The difference between this weight and that after peroxide treatment and washing represents the hydrogen-peroxide solution loss. The first dry weight is

[6] A tank with openings in the top to permit insertion of the beakers used, and having a steam connection for applying a constant low heat.

taken as the base for calculation of results except when the analysis is to be used for textural classification, in which event the dry weight after washing is used.

From the dry weight of the first pipetted sample, after deducting the weight of sodium oxalate in 25 cc of suspension, the dry weight of silt and clay in the sedimentation chamber may be directly determined. This is done by multiplying the dry weight of the pipetted sample by a factor equal to the ratio of the total volume of the suspension to the volume of the pipette. In routine analyses the weight of silt and clay in the cylinder is determined by the difference in the weight of the sample before dispersion and the dry weight of the material retained on the 300-mesh sieve. The weight determined by pipetting is used as a check, the maximum allowable difference being 2 percent.

The total weights of clay and fine clay are determined from the dry weight of the second and third pipetted samples in the same manner as that used in the determinations of clay and silt from the first pipetted sample. If the weight of clay is deducted from the total dry weight in the sedimentation chamber, the difference is silt. This, added to the silt sifted from the sand, gives total silt.

MODIFIED METHOD USED IN BUREAU LABORATORY

The modified pipette method of analysis used in the Bureau of Public Roads laboratory differs from the standard method just described in several respects as follows:

1. A sample of soil weighing 50 grams is used in the Bureau method, whereas but 10 grams of soil are used in the standard method. The volume of the suspension in each case is 1 liter.
2. The sample is freed from organic matter in the standard method, and but partially freed of this material in the Bureau method.
3. The sample is washed free of all water-soluble material in the standard method, but not in the Bureau method.
4. The sample is dispersed by a mechanical shaking of the container in the standard method, and by agitation within the suspension itself in the Bureau method.
5. The deflocculating agent used in the standard method is sodium oxalate; in the Bureau method, sodium silicate.
6. In the Bureau method the entire sample is placed in the sedimentation cylinder, the sand being separated by means of a fine sieve following the sedimentation.
7. In the Bureau method, sampling of the suspension immediately after dispersion is omitted. In addition to the clay and colloid fractions, the percentages finer than 0.040 millimeter and 0.001 millimeter are determined by pipetting in the Bureau method, but not in the standard method.

BEAKER METHOD DESCRIBED

The beaker method of analysis is performed as follows:

At the completion of the hydrometer test the suspension is transferred from the testing cylinder into a beaker of 1,000 cc capacity, and the soil again brought into suspension by stirring with a stiff brush. After a given time, T_1, in this case 52 minutes (at 25° C.), the top 8 cm of the suspension is decanted carefully into a large bottle. The decanted liquid contains no particles with diameters greater than d_1, the diameter of the particle which, according to Stokes's Law, settles 8 cm in the suspension in the time, 52 minutes, noted above. The portion of the suspension remaining in the beaker contains all particles of greater diameter than the calculated one (0.005 mm in this case) together with those of lesser size whose settling velocities and distance of settlement were sufficient to carry them below the upper 8 cm of the suspension in the time T_1.

The volume of the suspension in the beaker is brought to 1,000 cc with distilled water, the suspension is again stirred with a brush and after 52 minutes the top 8 cm are again decanted into the bottle mentioned above.

This process is continued until the decanted water is clear after 52 minutes' sedimentation, indicating that all material finer than 0.005 mm (clay) has been washed out. The total amount of this fraction is determined by evaporating a representative sample of the washwater to dryness.

The washing and decantation are continued, with successive sedimentation periods of 26.5, 13.0, and 3.25 minutes to remove, respectively, the fractions of size 0.005 to 0.007 mm, 0.007 to 0.010 mm, and 0.010 to 0.020 mm, the amount of each of these fractions being determined in the same manner as in the case of the clay.

The material coarser than 0.020 mm (sediment from the last washing) is dried and separated into two fractions by a no. 200 sieve. In the present instance the total of the determined fractions checked the original weight of the sample within one percent.

As has been shown, the pipette, beaker, and hydrometer methods are all based on Stokes's formula as applied to sedimentation of particles through water. Nevertheless, these sedimentation methods differ widely from the hydrometer method in the application of Stokes's law. Differences in test procedures prevent an exact agreement of results given by different sedimentation methods.

In the sedimentation methods the values of L are definite, being equal to the distance from the surface of the suspension to the level from which the sample is pipetted, or to which the suspension is decanted. In the hydrometer method, in contrast, the values of L are not definite but must be assumed on the basis of some relation to the elevation of the hydrometer in the suspension.

Furthermore, it has been shown that differences in the treatment of the sample and the method of dispersion may cause differences in results. Thus, for instance, the clay contents indicated by the procedure of the Bureau of Chemistry and Soils and by the beaker method were found to be slightly higher than those furnished by pipetting samples of the suspension used in the hydrometer test.

In the hydrometer method of analysis, therefore, no one value of L can be considered exact for all soils, but instead a compromise among several values indicated desirable by various investigations must be employed. Furthermore, the values of L suitable for a hydrometer of one shape may not be suitable for hydrometers of a different shape. Finally, in the case of uniformly graded soils, the value of L may change appreciably without affecting materially the practical value of the results.

It has been found that an L for the specific gravity hydrometer equal to the distance from the surface of the suspension to the center of volume of the hydrometer and one equal ot 0.60 of this distance for the Bouyoucos hydrometer may serve to give results in substantial agreement with those given by the selected value of L previously discussed (p. 98). This is illustrated in table 8. The different values of L used in table 8 are shown in table 9.

TABLE 8.—*Clay and fine-clay contents determined by use of various values of L in Bouyoucos and specific gravity hydrometer tests*

Soil no.	Below 0.005 mm				Below 0.002 mm			
	Bouyoucos hydrometer		Specific gravity hydrometer		Bouyoucos hydrometer		Specific gravity hydrometer	
	0.42× HD [1]	0.60× CV [2]	0.62× HD	1.00× CV	0.42× HD	0.60× CV	0.62× HD	1.00× CV
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	12	12	13	13	8	8	10	10
2	28	28	28	28	17	17	17	17
3	32	32	34	34	26	26	27	27
4	40	40	41	39	29	29	30	30
5	44	44	44	44	33	33	33	33
6	57	57	54	53	37	36	36	36
7	80	81	77	77	62	63	60	60
8	86	87	87	87	64	64	61	61

[1] Total immersed depth.
[2] Depth of center of volume.

TABLE 9.—*Depths corresponding to different values of L for various hydrometer readings*

Bouyoucos hydrometer			Specific gravity hydrometer		
Hydrometer reading	L=0.42× immersed depth	L=0.60× depth of center of volume	Hydrometer reading	L=0.62× immersed depth	L=depth of center volume
	Cm	*Cm*		*Cm*	*Cm*
0	10.0	12.3	1.000	15.0	16.4
10	9.2	10.9	1.010	13.9	14.7
20	8.5	9.6	1.020	12.8	13.0
30	7.8	8.5	1.030	11.8	11.3
40	7.1	7.3	1.040	10.8	9.6
50	6.4	6.2	1.050	9.8	7.9

TABLES SHOW AGREEMENT OF HYDROMETER METHOD WITH OTHER METHODS OF MECHANICAL ANALYSIS

The agreement of the results given by the hydrometer method with those given by other methods is shown in tables 10, 11, and 12.

TABLE 10.—*Comparison of analyses by (1) Bouyoucos hydrometer (L=0.42 HD) and (2) pipette method (Bureau of Chemistry and Soils Laboratory)*

Soil no.	Percentage finer than—					
	0.050 mm		0.005 mm		0.002 mm	
	(1)	(2)	(1)	(2)	(1)	(2)
487	57.5	56.7	18.0	16.4	13.8	10.7
630	80.6	83.3	39.8	40.7	27.0	26.1
659	76.5	78.9	22.1	20.8	15.1	14.7
695	82.5	84.7	47.0	47.6	35.5	38.3
763	68.8	66.7	35.6	37.9	25.8	30.3
802	98.6	99.6	78.1	78.1	54.0	57.4
837	94.1	95.0	75.0	71.9	64.1	61.9
872	88.0	88.9	44.8	40.6	26.1	29.3
4258	81.0	84.9	21.2	22.2	13.6	11.3
4295	95.0	96.7	38.0	32.3	29.2	27.8
4907	11.6	12.5	7.5	9.0	6.5	3.9
4913	58.5	55.6	24.2	27.2	14.4	19.3
Average deviation from (2)	−0.9	.....	+0.6	.....	−0.5	.....
Maximum deviation from (2)	−3.9	.....	+5.7	.....	−4.9	.....

Table 10 gives the results of the hydrometer tests and of pipette analyses by the method of the Bureau of Chemistry and Soils, together with the average and maximum deviations in percentages of the different sizes.

Here the comparison of the hydrometer test results with those of the particular method noted shows agreement within 1 or 2 percent in the majority of cases. Only in very exceptional cases does the variation exceed 5 percent. This agreement with the pipette method is entirely satisfactory for all practical purposes.

Tables 11 and 12 show that the hydrometer results are approximately 3 percent higher on the average than those given by the modified pipette method and between 1 and 2 percent higher than those given by the beaker method.

TABLE 11.—*Comparison of analyses by (1) Bouyoucos hydrometer (L=0.42 HD), (2) Specific Gravity hydrometer (L=1.00 CV) and (3) pipette method (Bureau of Public Roads laboratory)*

Soil no.	Percentage finer than—											
	0.040 mm			0.005 mm			0.002 mm			0.001 mm		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
5782	98.0	98.0	97.2	86.3	86.7	83.5	63.8	61.6	59.0	43.1	38.5	39.
5822	58.0	57.1	57.2	40.2	39.0	35.5	29.2	30.1	27.3	23.7	26.2	21.7
5833	70.8	70.0	67.3	27.6	28.0	24.0	17.1	16.8	14.6	11.4	12.0	9.7
5838	94.5	93.5	91.0	56.8	53.1	36.8	35.7	32.3	27.1	27.1	25.1	23.3
5842	74.1	72.0	70.6	32.0	34.2	30.9	26.0	27.0	25.2	21.2	22.0	18.7
5854	94.0	95.2	93.6	80.1	77.1	76.8	62.6	59.8	56.8	45.2	43.2	41.9
6062	35.2	32.0	29.2	12.5	13.0	9.8	8.0	9.7	6.0	6.5	6.0	3.7
6098	78.1	77.0	75.4	44.0	43.8	40.0	33.0	33.1	29.0	25.3	25.5	22.0
Average deviation from (3)	+2.6	+1.7	.....	+3.6	+3.0	.....	+3.2	+3.1	.....	+2.8	+2.3	.....
Maximum deviation from (3)	+6.0	+2.8	.....	+6.5	+4.0	.....	+5.2	+4.2	.....	+3.8	+4.5	.....

TABLE 12.—*Comparison of analyses by (1) Bouyoucos hydrometer (L=0.42 HD) and (2) beaker method*

Soil no.	Percentage finer than—							
	0.020 mm		0.010 mm		0.007 mm		0.005 mm	
	(1)	(2)	(1)	(2)	(1)	(1)	(1)	(2)
558	25.2	25.3	20.0	20.1	17.5	17.1	15.5	16.0
559	50.8	47.5	36.5	34.6	30.8	29.5	25.8	25.4
560	70.5	69.5	56.5	57.9	51.4	50.8	45.2	45.4
561	65.7	64.6	53.0	52.0	46.5	45.0	41.0	40.0
562	48.6	49.4	35.4	34.9	30.0	28.4	25.5	25.8
563	59.0	55.1	46.0	41.6	40.2	35.9	35.0	33.8
564	55.5	52.6	43.0	40.2	37.5	34.1	33.0	32.0
566	73.5	70.9	58.0	55.3	49.5	47.8	43.2	42.8
Average deviation from (2)	+1.7	.....	+1.5	.....	+1.9	.....	+0.4	.....
Maximum deviation from (2)	+3.9	.....	+4.4	.....	+4.3	.....	+1.2	.....

This lack of agreement has little significance, however, as neither of the two methods are at present standard procedures. The results shown in these tables were obtained as a part of this investigation and are included principally to disclose the lack of agreement between these two methods and the pipette method. If all three methods were in agreement, no change from the standard value of L would be required.

TABLE 13.—*Comparison of analyses by (1) Bouyoucos hydrometer (L=0.70 HD), (2) specific gravity hydrometer (L=HD) and (3) pipette method (Bureau of Public Roads laboratory)*

Soil no.	Percentage finer than—											
	0.040 mm			0.005 mm			0.002 mm			0.001 mm		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
5782	97.8	97.1	97.2	80.6	80.2	83.5	56.2	53.7	59.0	35.3	32.0	39.6
5822	55.0	54.5	57.2	37.2	36.2	35.5	27.5	29.1	27.3	21.5	24.7	21.7
5833	65.0	63.7	67.3	24.7	25.4	24.0	15.1	16.0	14.6	9.5	10.2	9.7
5838	92.2	92.5	91.0	50.9	48.6	50.3	33.2	33.0	32.3	23.8	23.0	23.3
5842	64.1	60.5	70.6	30.2	32.3	30.9	24.2	25.4	25.2	19.8	20.7	18.7
5854	93.0	95.0	94.6	75.9	74.0	76.8	56.0	55.0	56.8	39.0	39.0	41.9
6062	28.3	28.5	29.2	10.2	12.5	9.8	7.4	9.0	6.0	5.6	5.9	3.7
6098	74.5	73.8	75.4	40.8	41.2	40.0	31.5	31.5	29.0	24.0	24.1	22.0
Average deviation from (3)	−1.4	−2.0	.....	−0.1	−0.1	.....	+0.1	+0.3	.....	−0.3	−0.1	.....
Maximum deviation from (3)	−1.4	−2.0	.....	−0.1	−0.1	.....	+0.1	+0.3	.....	−0.3	−0.1	.....
	−6.5	−10.1	.....	−2.9	−3.3	.....	−2.8	−5.3	.....	−4.3	−7.6	.....

As a matter of fact, however, the significance of the difference of results furnished by the different methods is indicated by the different values of L as shown in tables 13 and 14.

TABLE 14.—*Comparison of analyses by (1) Bouyoucos hydrometer ($L=0.49\ HD$) and (2) beaker method*

Soil no.	Percentage finer than—							
	0.020 mm		0.010 mm		0.007 mm		0.005 mm	
	(1)	(2)	(1)	(2)	(1)	2()	(1)	4 (2)
558	24.3	25.3	19.8	20.1	17.0	17.1	14.8	16.0
559	49.4	47.5	35.2	34.6	29.6	29.5	24.6	25.4
560	68.8	69.5	55.4	57.9	50.0	50.8	44.0	45.4
561	64.2	64.6	51.6	52.0	45.2	45.0	40.0	40.0
562	47.2	49.4	34.4	64.9	28.8	28.4	24.2	25.8
563	57.6	55.1	44.8	41.6	39.0	35.9	33.6	33.8
564	54.0	52.6	41.8	40.2	36.4	34.1	32.0	32.0
566	72.0	70.9	56.4	55.3	48.2	47.8	42.0	42.8
Average deviation from (2)	+0.3	.....	+0.4	.....	+0.7	.....	−0.8	.....
Maximum deviation from (2)	+2.5	.....	+3.2	.....	+3.1	.....	−1.6	.....

SUMMARY

However elaborate the method, no mechanical soil analysis based on Stokes's formula is capable of yielding an exact determination of the particle size distribution. In fact the results of such analyses are to a large extent dependent upon certain arbitrary conditions of test. A basis for estimating the relative accuracy furnished by the various test methods does not exist. Their efficiency must be determined upon the basis of the time and effort required for performing the tests and the scope of the data obtained.

In the hydrometer method, as in all other methods of mechanical soil analysis based on sedimentation of soil particles through water, thorough dispersion of the soil sample is desirable. The apparatus specified in the procedures, especially with the added improvements discussed in this report, is highly efficient for this purpose, and in conjunction with the supplementary treatments determined according to the plasticity of the soil, provides the necessary degree of dispersion with a minimum of time, attention, and effort.

A high degree of deflocculation or maintenance of the separation of the suspended particles is also of importance to the success of the test, and, with few exceptions, is adequately effected by use of the deflocculating agent specified in the procedures.

Readings of a sensitive hydrometer in soil suspensions serve very adequately to produce the data required for the determination of the grain size distribution in subgrade soils.

In the use of Stokes's formula as applied to the hydrometer test data, the values of L equal (1) to 0.42 of the total immersed depth of the Bouyoucos hydrometer, and (2) to the depth of the center of volume of the specific gravity hydrometer yield satisfactory results in the mechanical analysis of subgrade soils.

The variations of test conditions from those which the use of Stokes's formula assumes, combined with the fact that the value of L is not critical in many cases, may cause one to question the need of all the refinements included in the testing procedure as published.

For average soils tested under average conditions, the clay content based on the Bouyoucos hydrometer reading at 60 minutes, with hydrometer readings properly corrected for temperature and specific gravity and the fine clay content based on readings of the same hydrometer at 370 minutes are likely to be fairly accurate. If the specified refinements required appreciable time and effort, the desirability for making them for average soils would be open to serious question if only approximate results were wanted and the soil accumulation curve were not required.

These refinements are necessary in the analysis of unusual soils, however, and do increase the accuracy of tests on ordinary soils. They must, therefore, of necessity be included in any general procedure. Furthermore, by means of the graphical method of solution all of the corrections can be made without increasing noticeably the effort required to perform the tests.

The hydrometer method is not confined to the use of a hydrometer of any one type or calibration; the principal requirement is merely that the hydrometer shall be sensitive enough to measure the density of soil suspensions with an accuracy sufficient to give a reasonably close determination of the percentage of suspended soil. The relation between density of suspension and percentage of suspended soil expressed by equation 3 offers a basis for transforming the readings of any hydrometer into terms of soil percentage.

The depth of settlement, L, for use in Stokes's formula, which is likely to vary with different shapes of hydrometer bulbs, must be determined for any type of hydrometer other than those described in this report. This may be done on the basis of the relation between the hydrometer test data and the percentages of the different fractions furnished by some desired method of mechanical analysis or on the basis of results furnished by a hydrometer which has been standardized.

In spite of the fact that the depth of settlement, L, is a variable for which no one correction can be universally applied, the hydrometer test as used by the Bureau of Public Roads yields, with minimum effort, results which are in substantial agreement with those furnished by the more elaborate pipette method.

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EFFECT OF CURING CONDITIONS ON THE STRENGTH OF CEMENT MORTAR

Reported by D. O. WOOLF, Associate Materials Engineer, and K. F. SHIPPEY, Junior Highway Engineer, Division of Tests, United States Bureau of Public Roads

A TENDENCY for portland-cement-mortar specimens, particularly the standard 1:3 briquets, to retrogress in strength with age when stored in water has been noted many times. Since a corresponding retrogression in the strength of concrete specimens stored in moist air is rarely found, it has generally been assumed that the reduction in strength is not due to any defect in the cement but rather to some feature or treatment involved in the method of test. An explanation which has been advanced is that retrogression is due to the solution of a part of the cement by the storage water. If this is true, the reason for the decrease in strength of specimens stored in running water would be explained.

To determine if this theory is correct, an investigation of the effect of curing conditions on the strength of cement mortar was recently undertaken by the Bureau. Both briquets and 2-inch cubes were prepared with four different cements, including one high-early-strength cement. The briquets were made in accordance with American Society for Testing Materials Standard Method C 77–30, and the cubes were prepared essentially as described in a paper by E. M. Brickett, American Society for Testing Materials Proceedings, 1928, part II.

A mix of 1:2.75 by weight was used in the preparation of the cubes with a water-cement ratio of 0.53 by weight (0.80 by volume). The sand used is designated as "run-of-mine Ottawa sand" from Ottawa, Ill., and consists of the material from which standard Ottawa sand is obtained. Tests for consistency made on the 10-inch flow table using thirty ⅛-inch drops in 30 seconds gave a flow of approximately 90 percent with the above mixture. To insure uniform preparation of the test specimens, 54 cubes, or briquets, were molded in 1 day with a single cement. This furnished sufficient specimens for one series of tests at all ages with each condition of storage. After curing for 24 hours in the moist closet, each series of 54 specimens was separated at random into 3 sets of 18 specimens each. One set for each of the four cements was stored until date of test under each of the following conditions:

1. In running water
2. In still water
3. In moist air.

VARIATION OF STRENTH WITH AGE STUDIED

Tests were made at ages from 7 days to 1 year on both types of specimens cured under each of the above conditions of storage. All specimens were broken in a wet condition, the specimens cured in moist air being placed in still water for 24 hours immediately prior to test. Three series of specimens of each type were made with each of the normal portland cements, and two series with the high-early-strength cement, each series containing 54 specimens of each type.

The results of these tests are shown in the accompanying figures. Each point is the average of 9 individual tests in the case of the normal cements and 6 tests in the case of the high-early-strength cement.

The three normal portland cements exhibit in general the same characteristics. In the tension tests, the briquets stored in both running and still water show either retrogression or little change in strength after 28 or 90 days. Cement 3 shows a marked retrogression after 90 days, which continues to the age of 1 year. Cements 1 and 2 show retrogression after 28 days, this being most marked in the case of the running-water specimens for cement 1. The briquets cured in moist air show in two cases a steady increase in strength to the last testing period. In the case of cement 1, the moist-air specimens increase in strength to an age of 90 days, show a slight decrease in strength to an age of 270 days, and then recover strength at 1 year to exceed slightly the maximum obtained at an earlier period.

The tension specimens prepared with high-early-strength cement and cured in water or moist air develop retrogression after ages of 28 or 90 days. This is very marked for the briquets cured in both running and still water. The moist-air specimens show a small decrease in strength after 90 days and hold this strength to 1 year.

The compression tests of the normal portland cements show, as a general rule, an increase in strength to an age of 270 days for all wet storage conditions followed by little change in strength at 1 year. In the case of cement 3 the specimens cured in still water give some erratic results which cannot be explained at present. The compression tests made on the high-early-strength cement show a continual decrease in strength after 28 days for the specimens cured in running water, while the specimens cured in still water attain a maximum strength at 90 days and hold this strength at later periods. The specimens cured in moist air increase in strength to 180 days after which the strength is reduced considerably.

The results of these tests show that cement-mortar briquets used in the tensile strength test are usually subject to retrogression after ages of 28 days to 180 days when cured in water, either running or still. Briquets stored in moist air are usually found to show a steady increase in strength for ages up to 1 year, but the 7- and 28-day strengths are appreciably lower than those of the water-cured specimens. Briquets made with high-early-strength cement and stored in water or moist air show more marked retrogression in strength at an earlier age than is found for normal portland cement.

Little retrogression is found in the compression tests of normal portland-cement mortars. A definite retrogression in compressive strength, however, is found for high-early-strength cement specimens cured in running water, and those cured in still water fail to increase in strength after 90 days.

LOSS OF STRENGTH ATTRIBUTED TO SOLUTION OF PART OF CEMENT IN STORAGE WATER

The retrogression in strength found in small specimens of portland-cement mortar has been attributed to the solution and removal of a part of the cement by

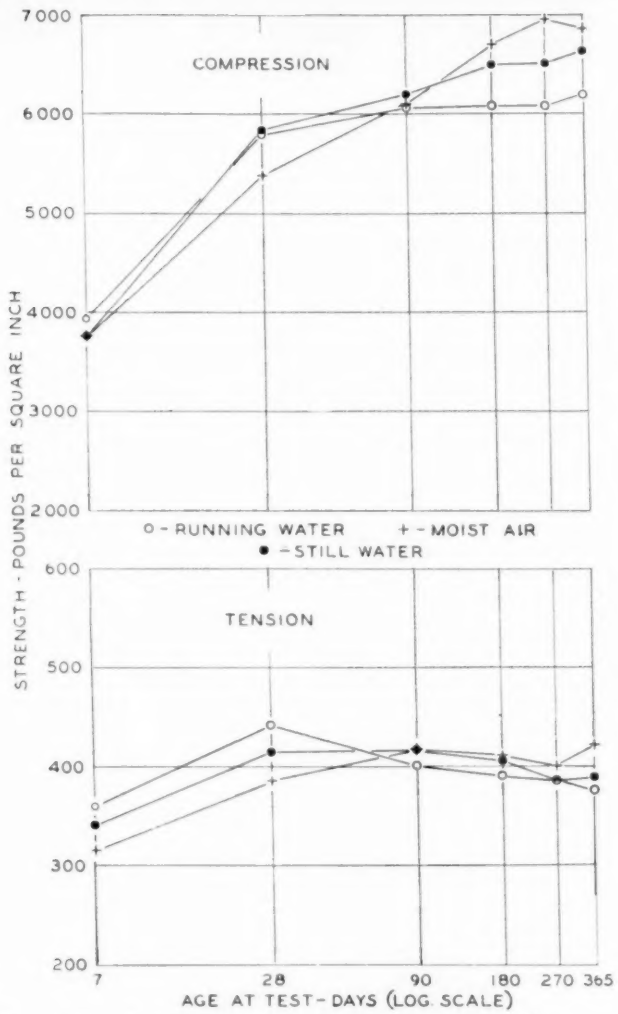

FIGURE 1.—STRENGTHS OF CUBES AND BRIQUETS MADE WITH NORMAL PORTLAND CEMENT NO. 1.

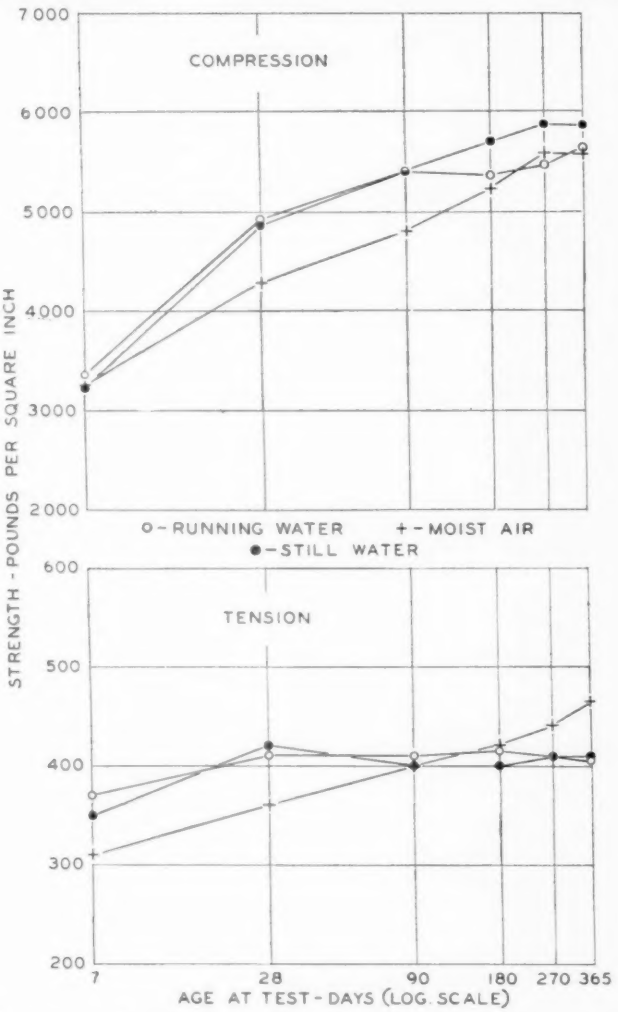

FIGURE 2.—STRENGTHS OF CUBES AND BRIQUETS MADE WITH NORMAL PORTLAND CEMENT NO. 2.

the storage water. This theory is believed to be substantiated by these tests. In this series of tests the conditions which might affect the strength were the same for all specimens except the medium in which they were stored. The occurrence of retrogression to the greatest extent in the water-cured specimens is indicative of the nature of the weakening action, that is, by solution of a portion of the cement. The still-water specimens were stored in an open pan, and frequent additions of water were necessary to replace that lost by evaporation. It is believed that the retrogression found in the still-water specimens would have been considerably smaller if the specimens had been stored in covered containers with a minimum of water. The fact that retrogression is found in the compression tests at a later date and to a lesser degree than in the tension tests is attributed to the difference in size and shape of the specimens used. If each type of specimen were subjected to the same solvent action of water, the briquet would be affected to the greater extent due to its smaller cross section.

TESTS FAIL TO CONFIRM THEORY ATTRIBUTING LOSS OF TENSILE STRENGTH TO UNEQUAL STRESS DISTRIBUTION IN BRIQUET

In the first report of the Joint Conference on Uniform Methods of Tests and Standard Specifications for Cement [1] the retrogression of strength found in cement mortar briquets is attributed to the inequality of stresses set up in a briquet by the method of loading coupled with the rigidity of the specimen. The load applied at four points by the clips must be transmitted in a very short distance to the entire cross section of the briquet and it is claimed that a uniform distribution of this stress over the minimum section is impossible. Prof. J. B. Johnson concluded from an analytical study of the problem that the maximum stress in a briquet of

[1] Committee C-1, A.S.T.M., Data Book, published by the committee, section II, p. 74, July 1919.

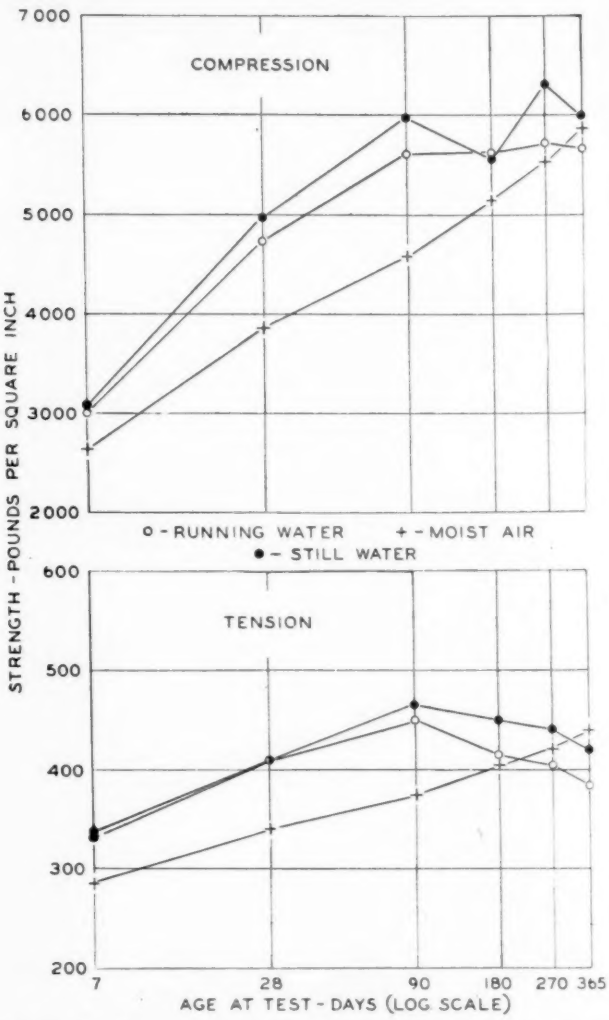

FIGURE 3.—STRENGTHS OF CUBES AND BRIQUETS MADE WITH NORMAL PORTLAND CEMENT NO. 3.

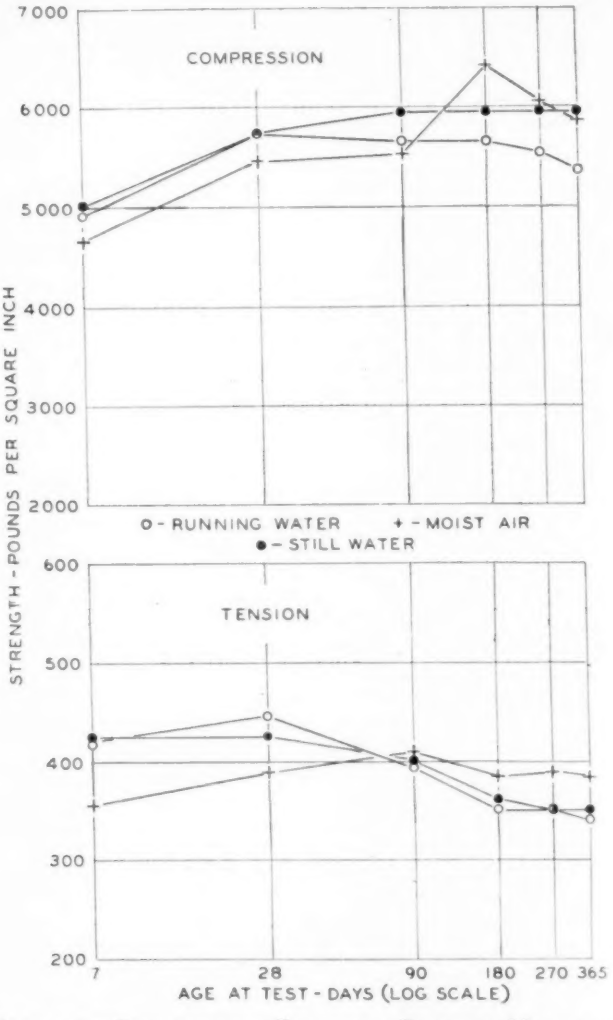

FIGURE 4.—STRENGTHS OF CUBES AND BRIQUETS MADE WITH HIGH-EARLY-STRENGTH CEMENT NO. 4.

the form now used is about 1.54 times the minimum stress. E. G. Coker made an experimental determination of stresses in briquets, using the effect of polarized light passing through models of transparent celluloid, and concluded that the highest stress in the minimum section of the test specimen is 1.75 times the mean stress. With a very rigid material the opportunity for an adjustment of stresses within the specimen is much less than in a material of low rigidity. According to this theory a very high stress is developed in the older briquets at the edges of the section during the first stages of loading, and a tearing action is produced which results in rupture at a lower stress than would have been withstood at an earlier age when the lower rigidity permitted of a more uniform distribution of stress.

The results obtained in this investigation do not seem to be in agreement with the above theory. The briquets cured in moist air show a steady increase in strength. According to the theory, the specimens at age of 270 or 365 days should fail at a lower load than the 7- or 28-day specimens. Such is not found and the conclusion is reached that this theory is incorrect.

TESTS INDICATE STANDARD CURING PRACTICE SATISFACTORY

The present standard specifications for testing portland cement require that the specimens be cured in water. These tests, involving a limited number of observations, do not show any reason for changing from the standard practice of curing mortar specimens for ages up to and including 28 days. Little preference is seen between running- and still-water storage, as specimens stored under either condition develop essentially the same strength at 7 or 28 days. The moist-air storage is, however, recommended for tests of mortar specimens at greater ages.

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TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio. (1927.)

Report of a Survey of Transportation on the State Highways of Vermont. (1927.)

Report of a Survey of Transportation on the State Highways of New Hampshire. (1927.)

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio. (1928.)

Report of a Survey of Transportation on the State Highways of Pennsylvania. (1928.)

Report of a survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States. (1930.)

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS may be obtained upon request addressed to the U.S. Bureau of Public Roads, Willard Building, Washington, D.C.

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UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

CURRENT STATUS OF FEDERAL-AID ROAD CONSTRUCTION

AS OF

JULY 31, 1933

STATE	COMPLETED MILEAGE	UNDER CONSTRUCTION						APPROVED FOR CONSTRUCTION					BALANCE OF FEDERAL AID FUNDS AVAILABLE FOR NEW PROJECTS	STATE
		Estimated total cost	Federal aid allotted	Percentage completed	MILEAGE			Estimated total cost	Federal aid allotted	MILEAGE				
					Initial	Stage[1]	Total			Initial	Stage[1]	Total		
		$	$					$	$				$	
Alabama	2,355.6	4,742,320.50	2,371,160.14	86	119.9	110.2	230.1						3,199,828.75	Alabama
Arizona	1,880.6	2,820,591.84	1,320,741.91	93	57.7	126.8	184.5	59,134.40	31,023.48		6.1	6.1		Arizona
Arkansas	1,945.1	4,339,962.17	2,055,467.95	79	118.8	87.4	206.2	1,227,502.40	613,567.11	102.0	16.0	118.0	661,199.03	Arkansas
California	2,534.0	6,407,652.46	1,528,062.16	85	126.4	32.1	158.5	73,760.41	17,153.65	.9	2.0	2.9		California
Colorado	1,892.3	2,310,126.95	1,040,247.34	64	85.3	11.5	96.8	1,350,432.71	583,285.50	40.6	52.2	92.8	54,574.57	Colorado
Connecticut	299.5	4,037,365.34	1,659,219.49	83	41.0	5.3	46.3						183,167.11	Connecticut
Delaware	405.3	309,623.50	59,812.72	98	7.4	7.2	14.6							Delaware
Florida	663.6	5,425,056.85	2,576,211.42	81	158.0	11.5	169.5						1,008,446.01	Florida
Georgia	3,307.2	3,163,588.65	1,292,758.51	91	89.9	129.8	219.7						100,636.93	Georgia
Idaho	1,597.1	2,381,148.88	859,613.66	83	85.3	113.9	199.2	138,413.39	66,374.60	5.7	26.8	32.5	40,793.01	Idaho
Illinois	3,143.7	19,142,650.18	7,158,083.12	78	590.9	60.6	651.5	587,949.56	290,001.86	20.5		20.5	95,967.25	Illinois
Indiana	2,122.1	8,169,261.24	2,932,592.03	88	278.2	21.9	300.1	609,598.98	98,177.17	20.1	3.0	23.1		Indiana
Iowa	3,677.4	2,876,157.82	343,197.16	90	140.2	14.3	154.5						27,848.05	Iowa
Kansas	4,071.5	3,260,041.34	933,948.55	74	187.7	50.4	238.1	299,371.96	106,403.33	89.9	13.8	103.7	15,535.08	Kansas
Kentucky	1,969.2	3,895,175.12	1,402,517.10	79	157.5	97.0	254.5	104,198.71	46,331.37	2.4	8.7	11.1		Kentucky
Louisiana	1,682.9	6,281,251.44	2,735,866.90	71	38.9	24.8	63.7						4,190.58	Louisiana
Maine	832.5	1,817,536.30	459,411.28	74	55.2	2.2	57.4							Maine
Maryland	874.1	830,173.77	93,860.77	91	32.0	1.5	33.5	263,878.40	85,673.37	5.4		5.4		Maryland
Massachusetts	876.4	4,115,901.96	972,218.48	83	57.2	4.9	62.1						339,016.29	Massachusetts
Michigan	2,416.2	5,632,625.42	2,119,097.45	80	253.8	71.7	325.5	141,300.00	50,705.00	11.7		11.7	198,533.35	Michigan
Minnesota	4,309.6	4,759,578.15	206,528.91	98	151.0	139.9	290.9						30,504.16	Minnesota
Mississippi	1,862.5	6,539,603.92	3,245,253.58	73	179.4	112.9	292.3	81,968.58	40,984.17	3.2	3.4	6.6	2,791,831.23	Mississippi
Missouri	3,262.1	3,951,429.70	681,209.60	58	141.9	27.4	169.3	193,215.66	61,048.60	5.8	6.4	12.2		Missouri
Montana	2,951.6	6,171,603.82	3,442,620.60	89	414.5	246.1	660.6	197,566.09	111,137.88	.5	57.0	57.5	95,837.70	Montana
Nebraska	4,284.5	5,696,135.19	2,663,872.42	92	138.1	152.7	290.8						56,616.07	Nebraska
Nevada	1,344.2	2,083,553.46	658,660.73	97	20.7	152.9	173.6	159,568.45	79,784.22	9.9	33.9	43.8	61,164.81	Nevada
New Hampshire	450.7	536,710.27	214,442.76	81	11.4	.5	11.9	20,531.40	8,212.56	.4		.4	77,387.63	New Hampshire
New Jersey	637.9	5,309,569.73	1,735,318.97	93	55.6		55.6						138,625.11	New Jersey
New Mexico	2,456.7	873,698.58	345,122.59	92	40.3	35.3	75.6	72,488.96	39,868.43	7.2	1.6	8.8	88,872.49	New Mexico
New York	3,524.5	18,013,530.05	5,483,100.00	66	471.3	32.0	503.3						355,781.37	New York
North Carolina	2,379.9	4,941,170.70	2,477,828.15	82	492.1	28.1	520.2	247,056.89	123,528.41	43.0	.3	43.3	977,194.06	North Carolina
North Dakota	5,525.5	3,344,326.20	1,483,434.12	59	225.2	342.3	567.5	431,095.31	209,476.42	31.1	112.8	143.9	264,263.71	North Dakota
Ohio	3,094.6	7,020,159.85	1,794,804.93	83	142.4	51.7	194.1	401,335.00	156,207.96	7.8	.3	8.1	43,622.92	Ohio
Oklahoma	2,539.1	3,587,419.84	1,137,922.90	88	165.0	67.1	232.1	562,586.25	316,197.29	67.6	5.6	73.2	215,224.61	Oklahoma
Oregon	1,642.7	3,812,578.93	1,572,517.58	85	97.8	69.1	166.9	35,805.00	18,486.11	1.4		1.4	34,012.84	Oregon
Pennsylvania	3,321.4	8,835,667.49	2,447,528.83	83	304.1	14.0	318.1						4,331.58	Pennsylvania
Rhode Island	277.5	809,915.11	283,007.01	84	16.6	4.5	21.1						70,834.03	Rhode Island
South Carolina	1,962.5	3,419,613.38	1,280,542.73	93	161.2	154.7	315.9						9,543.92	South Carolina
South Dakota	4,304.1	3,222,473.45	1,315,670.92	90	261.6	202.8	464.4	211,412.66	93,100.65	8.1	27.9	36.0	169,101.27	South Dakota
Tennessee	1,784.1	3,692,462.69	1,845,510.43	80	115.0	24.8	139.8						576,790.79	Tennessee
Texas	8,237.5	13,607,288.12	4,331,725.34	85	496.3	425.5	919.8	649,349.26	180,684.47	22.7	11.7	34.4	4,313.20	Texas
Utah	1,317.2	1,751,085.18	738,600.09	87	111.7	26.6	138.3	246,126.94	104,802.54	19.6	12.5	32.1	730.62	Utah
Vermont	391.1	465,379.08	73,902.58	41	22.4	6.6	29.0	19,378.18	850.98	.3		.3	238.42	Vermont
Virginia	2,029.8	3,577,897.84	1,576,503.95	88	146.3	50.5	196.8	80,190.16	22,057.12	4.1		4.1	176,551.34	Virginia
Washington	1,340.2	2,891,680.79	849,320.63	83	100.0	9.7	109.7	223,273.36	34,000.00		8.0	8.0	3,356.82	Washington
West Virginia	933.0	2,676,604.45	1,100,437.50	83	99.5	14.7	114.5						18,882.07	West Virginia
Wisconsin	2,764.0	5,315,322.60	1,259,767.95	81	132.4	101.9	234.3	52,061.50	21,500.00		.9	.9		Wisconsin
Wyoming	2,188.3	2,528,229.84	858,695.48	97	207.2	137.9	345.1						153,262.89	Wyoming
Hawaii	121.5	1,056,210.46	840,299.35	59	85.1		85.1	87,664.50	89,302.55	.7		.7	485,620.83	Hawaii
TOTALS	109,124.8	222,452,313.10	79,848,439.07	81	7,625.7	3,617.2	11,242.9	9,207,913.97	3,538,526.78	532.6	410.9	943.5	12,874,192.06	TOTALS
Construction completed		178,046,000	65,063,000											
Balance uncompleted		44,406,000	14,781,000											

[1] The term stage construction refers to additional work done on projects previously improved with Federal aid. In general, each additional work consists of the construction of a surface of higher type than was provided in the initial improvement.

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